NuMI Extraction Channel Design

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Introduction

We have reviewed the 120 GeV/c MI-60 extraction channel design for NuMI with a perspective toward robust capability for clean beam extraction at the highest Main Injector intensities. Design of this channel is very similar to that for the MI-52 extraction to the P1 beam-line. This has provided the opportunity of comparing to current operational experience and benchmarking beam loss simulations to beam data.[i] For NuMI extraction the combined requirements of a very low loss primary beam transport along with 6 batch Main Injector operation provide much more severe constraints than for current 120 GeV/c extraction to P1.

MI-60 Extraction Simulation for Baseline Design

Detailed simulation using the STRUCT[ii] computer program has been done to project beam distributions and estimate beam loss through the MI-60 extraction channel. Inputs include magnet channel geometry, corrector magnet strengths and quadrupole displacements. Detailed parameters used are shown in Tables 1-5, including comparison with parameters for other MI injection and extraction regions.

Beam Distributions

For injection into the Main Injector, emittance at 95% is assumed equal to 12π mm.mrad. Simulations are done for extraction emittance at 95% of 25π and 40π. Beam distributions used are Gaussian to 3 σ, with a 1/r distribution between 3 and 4 σ. For simulation purposes, one percent of the total beam flux is taken to be in this beam tail region from 3 to 4 σ.

Extraction Simulation

Shown in Figure 1 is the extracted beam central trajectory in the horizontal plane for the baseline plan of two extraction kickers, with kicker current optimized to best match extraction channel apertures. As can be seen, the kicked beam experiences a large offset to the inside at Q604 and then moves to the outside to match the Lambertson extraction channel. Phase advance between kickers and Lambertsons is approximately 270 deg.

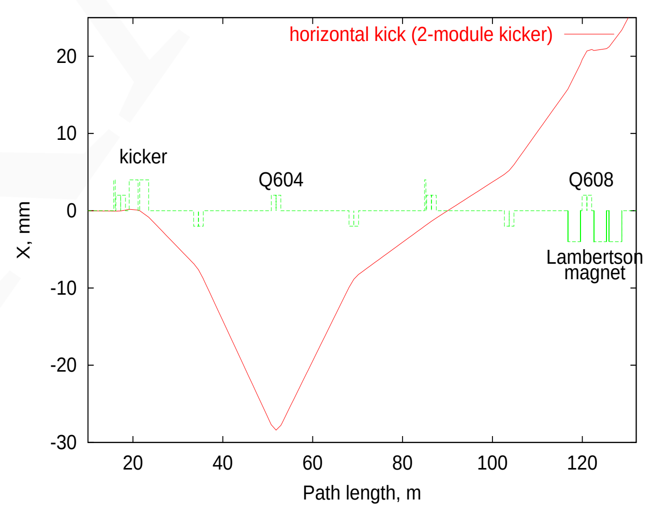


Fig. 1: Extracted beam central trajectory for baseline two module kicker.

Cross-section views with beam profiles are shown in Figure 2.a at two locations where extraction beam aperture concerns can be most severe. The top figure indicates beam profiles relative to the standard MI vacuum pipe at location of the Q604 quad, the point of largest beam excursion prior to the Lambertson string. As can be seen, beam positions vs. aperture are well matched, with no beam loss concern at this location. Shown in the bottom figure are the very considerable aperture constraints for beam extraction at location of Q608, between the first and second Lambertson magnets. The extraction beam emittance shown is 25π. Aperture constraints for the circulating beam exist due to both the conventional MI vacuum pipe and the inside channel of the Lambertsons. Extraction channel apertures are defined by the magnet septa edge on the inside, and the Q608 vacuum pipe both at the top and outside. Extraction channel of the Lambertson magnets is quite large, with gap width of 50 mm. However, the necessity of having a lattice quadrupole between Lambertsons reduces the effective channel aperture by as much as 70%. This is shown in Figure 2.b, where an expanded cross-section view at Q608 showing full system apertures is presented.

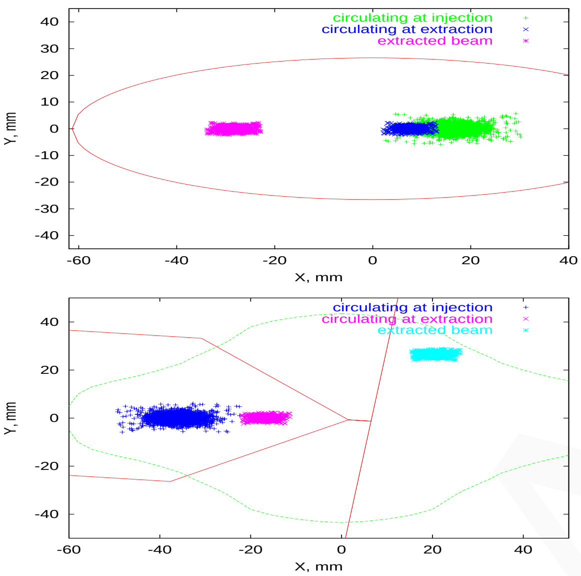


Fig. 2.a: [Left] Circulating and extracted beam at the Q604 center (top) and at the Q608 exit (bottom). Emittance (95%) is 12π mm.mrad at injection and 25π mm.mrad at extraction. Baseline two-kicker design.

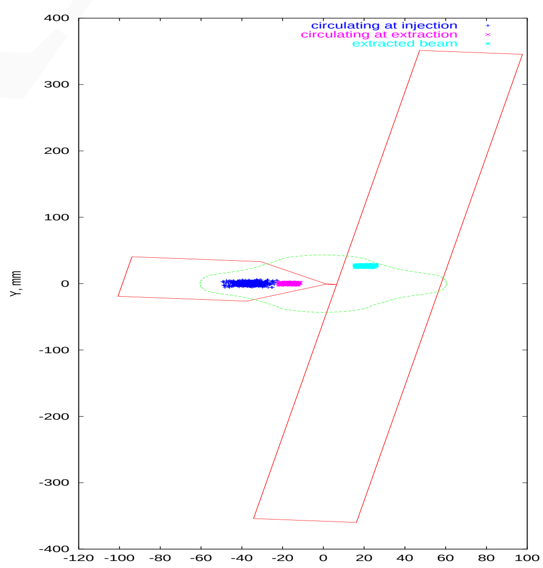


Fig. 2.b: [Right] Expanded cross-section view at the Q608 exit showing beam positions relative to Lambertson apertures. Baseline two-kicker design.

Fractional beam loss calculations have been done for variation of relevant parameters with the beam distributions described previously. Some results are displayed in Figure 3.a and b. In Fig. 3.a is plotted circulating (left edge) and extracted (right edge) 120 GeV beam loss as a function of the strength of the local bump produced by alignment displacement of quadrupoles between Q602–Q614. For a reduced quad bump, the circulating beam hits on the inside of the Lambertson septa; for a larger bump, the extracted beam hits on the outside of the septa. Kicker strength for this calculation is 1.46 kG-m with two kicker modules. A 120 GeV beam emittance of 25 π is used in this calculation.

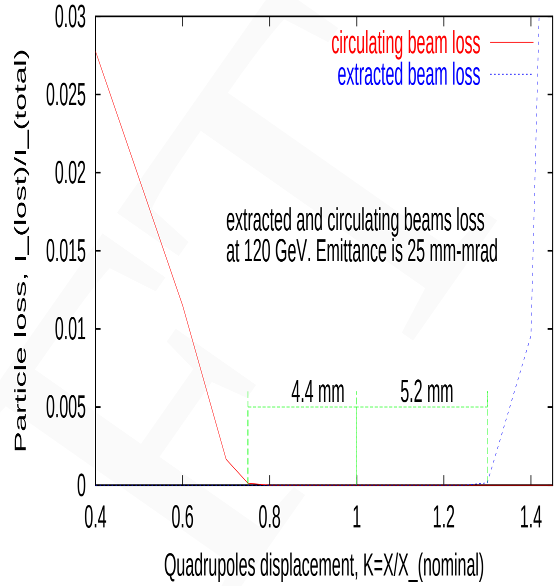


Figure 3.a

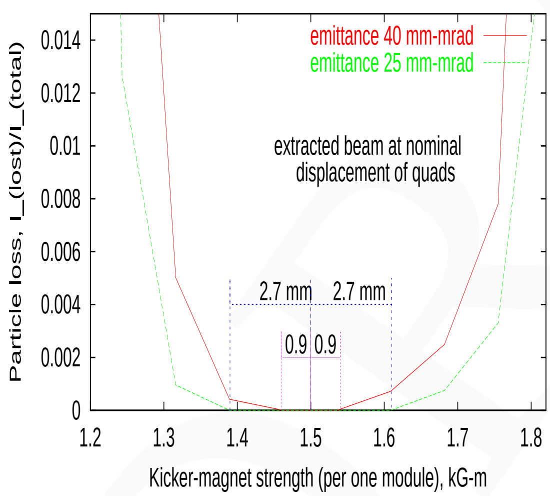


Figure 3.b

In Fig. 3.b, fractional beam loss is calculated, using nominal quad displacement, as a function of kicker magnet strength. Here the extracted beam loss is at the Lambertson septa for reduced kicker strength, and at Q608 for higher kicker strength. As can be seen in the figure the available extraction channel aperture is quite narrow. For a larger beam emittance of 40π, considered an appropriate design number[iii] for NuMI, aperture clearance becomes extremely tight, being less than 1 mm to either side for a beam tail distribution extending to 4 σ from beam center.

Kicker Constraints

Significant concern exists with the MI-60 extraction channel design, as modeled above, with extrapolation to MI beam parameters expected for NuMI operation. An additional major concern is that the “nominal” kicker strength of ~1.5 kG-m per module to center the extracted beam within the narrow channel is not at all nominal. Baseline kicker design is for two 1.99 m magnetic length modules, copies of the MI-52 kicker modules, with nominal integrated field per module of 1.12 kG-m (2250 A) and maximum capability of 1.38 Kg-m (2650 A).[iv] As can be seen from Figure 3.b, the nominal design kick of 1.12 kG-m for a two kicker design would lead to very major beam loss. The needed kick of ~1.5 kG-m per module is also significantly larger than the original projected maximum kicker capability.

Subsequent kicker design upgrade effort, with additional ferrite in each magnet and operating at a peak supply voltage of 63 kV can produce 1.5 kG-m per module[v], but without any operational range above this. In addition, robustness of controlled kicker firing is reduced at this power supply voltage.

Improved Extraction Channel Design

During Main Injector design, consideration was given[vi] for a larger aperture quadrupole design to address the aperture reduction imposed by the lattice quadrupole between Lambertsons. This would be a new magnet design effort, with significant performance specification requirements from the need to match existing quadrupole fields through the accelerator ramp. This can be an optimal long term solution, but seems not practical within schedule and cost constraints for NuMI.

Proposed here is a two part solution for the NuMI extraction channel design, which should be practical to implement and effectively addresses the current very limited extracted channel aperture.

Q608 Aperture Limit

To significantly move the extracted beam away from the Q608 aperture, a solution is reached by adding a second power supply to the Lambertson string, significantly reducing the field in the first magnet, and increasing field in the 2nd and 3rd magnets from the nominal 120 GeV value of 8.6 kG to an equivalent 150 GeV value of 10.7 kG. This higher field remains significantly below the maximum magnet design field of 12.3 kG. Magnet field parameters are shown in Tables 1 and 2, for the single vs. two power supply configurations, along with comparison to other MI locations. Beam height exiting the C-magnet after the 3rd Lambertson is now approximately 1 in. lower than for the baseline solution. A 3Q120 quadrupole of cross-section size 13” x 17” still fits above the MI beam pipe. Baseline design was to allow placement of a 15” x 17” quadrupole.

Kicker Strength

As noted above, a two kicker module solution is very marginal to achieve a viable separation at the MI-60 Lambertsons between circulating and extracted beams. A good solution is achieved by adding a 3rd kicker module, enabling a nominal kicker strength per module of 1.2 kG-m. This provides an appropriate kicker strength to position the extracted beam well away from the Lambertson septa aperture, given also the lowered field in the first Lambertson. Model simulation for this solution is presented below.

3 Kicker Extraction Simulation

A study was done of different placement options for a 3-kicker module solution, evaluating location both upstream and downstream of Q602. (2-kicker module placement is downstream of the quad.) Results are given in Figure 4, with the most effective placement being obtained by adding the 3rd kicker upstream of the quad and corrector. Tunnel insertion space also appears promising at this location.

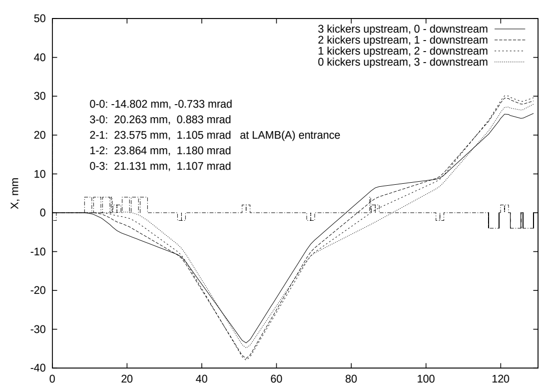
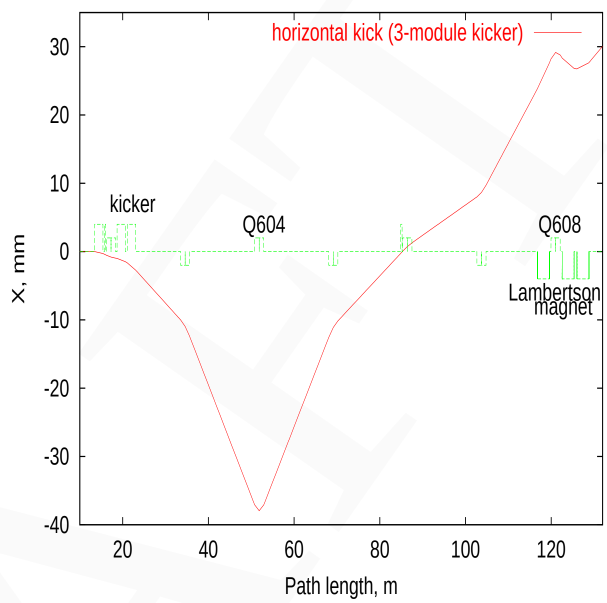


Figure 4.

A similar simulation study to that previously shown is now done for the dual power supply Lambertson configuration with three kicker magnets. Kicker and Lambertson parameters for this configuration are given in Table 2. Shown in Figure 5 is the extracted beam central trajectory in the horizontal plane from kicker location through the Lambertsons. In comparison to the 2-kicker trajectory in Figure 1, significantly greater extracted beam offset exists at the Lambertsons, but also at Q604.

Figure 5.



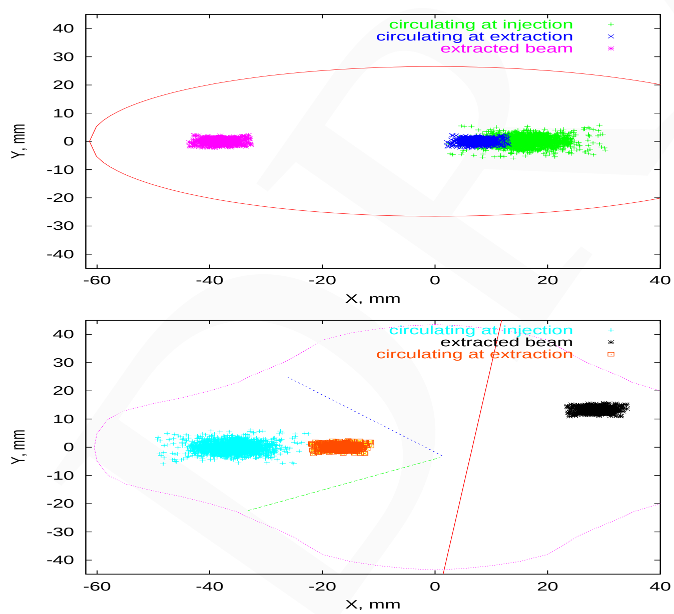


Figure 6.

A comparison of beam profiles is shown at Q604 and Q608 locations in Figure 6, which can be compared to Figure 2.a for the baseline solution. The extracted beam remains comfortably away from the vacuum pipe aperture in the Q604 region, and now has greatly expanded separation from both the Lambertson septa and the Q608 aperture.

Fractional beam loss calculations for the three kicker solution are done again as for the baseline solution, with results displayed in Figure 7.a and b. In Figure 7.a is plotted circulating (left edge) and extracted (right edge) 120 GeV beam loss as a function of the strength of the local bump produced by alignment displacement of quadrupoles between Q602–Q614. The extraction channel aperture has now been opened considerably in comparison to that for two kickers, shown in Figure 3.a. Kicker strength for this calculation is 1.2 kG-m per module with three kicker modules. A 120 GeV beam emittance of 25π is used in this calculation.

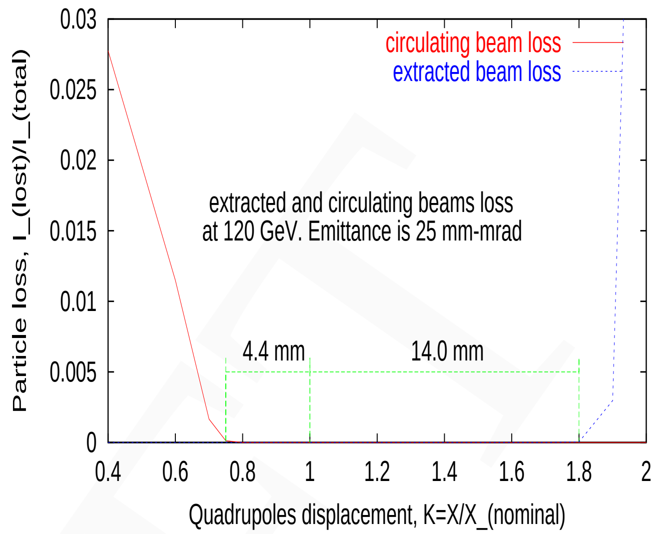


Figure 7.a.

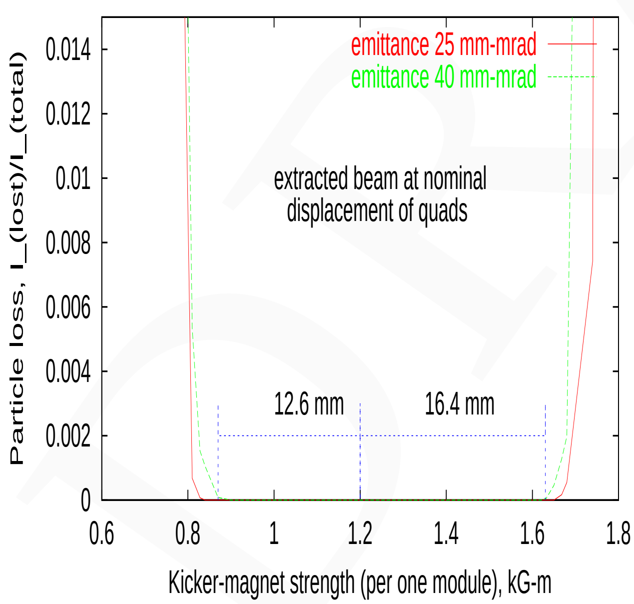


Figure 7.b.

In Figure 7.b, fractional beam loss is calculated for the three kicker solution, using nominal quad displacement, as a function of kicker magnet strength. Here the extracted beam loss is at the Lambertson septa for reduced kicker strength, and at Q608 for higher kicker strength. As can be seen in the figure the available extraction channel aperture is much larger than for two kickers, as shown in Figure 3.b. For the larger beam emittance of 40π, aperture clearance has been expanded by more than an order of magnitude to either side for a beam tail distribution extending to 4 σ from beam center. With the three kicker solution, an approximate match now also exists between the available extraction channel aperture, and the available aperture at Q604.

Summary

A solution has been developed for design of the NuMI MI-60 extraction channel which greatly expands aperture clearance for the high intensity NuMI extracted beam. Resource requirements are being developed, and appear relatively modest. Continued refinement is ongoing to optimize and finalize design parameters.

Table 1: Kicker and Lambertson magnet parameters for baseline MI-60 design, with comparison to other MI location parameters.

Kicker-magnets							
name	location	length	number	Max. kick	Max. field	field at 8 GeV	field at 120 GeV
		m		kG-m	kG	kG	kG
KM602A,B	**MI-60**	**1.99**	**2**	**1.4625**	**0.734925**		**0.734925**
K622A,B	MI-62	1.956	2				0.537182
K103A,B,C	MI-10	1.0922	3			0.093115	
K304	MI-30	1.956	1			0.166744	
K400	MI-40	1.89	2			0.079709	0.876225
K520	MI-52	1.9558	2			?	0.625831
Lambertson magnets							
name	location	length	number	Max. kick	Max. field	field at 8 GeV	field at 120 GeV
		m		kG-m	kG	kG	kG
LAM60A,B,C	**MI-60**	**2.8**	**3**	**34.6**	**12.357**		**8.5774**
LAM62A,B,C	MI-62	2.8	3	34.6	12.357		8.9
LAM10	MI-10	2.286	1			4.539610	
LAM222	MI-22	4.064	1		1.677	1.677	
LAM321	MI-32	4.064	1		1.677	1.677	
LAM40A,B,C	MI-40	2.8	3	34.6	12.357	0.555556	7.5
LAM52A,B,C	MI-52	2.8	3	34.6	12.357	?	9.3

Table 2: Kicker and Lambertson magnet parameters for three-kicker module solution.

Kicker-magnets							
name	location	length	number	Max. kick	Max. field	field at 8 GeV	field at 120 GeV
		m		kG-m	kG	kG	kG
KM602A,B,C	**MI-60**	**1.9558**	**3**	**1.2**			**0.613560**
Lambertson magnets							
name	location	length	number	Max. kick	Max. field	field at 8 GeV	field at 120 GeV
		m		kG-m	kG	kG	kG
LAM60A	**MI-60**	**2.8**	**3**	**34.6**	**12.357**		**4.2887**
LAM60B,C	**MI-60**	**2.8**	**3**	**34.6**	**12.357**		**10.72175**

Table 3: **Lambertson magnet septa position and rotation angle, with MI60 compared to other MI locations. Entrance and exit are for the proton direction.**

		septa position		
name	location	horizontal	vertical	rotation
		mm	mm	radian
LAM60A entr	**MI-60**	**3.2**	**-4.0**	**0.115**
LAM60A exit	**MI-60**	**3.2**	**-4.0**	**0.115**
LAM60B entr	**MI-60**	**4.0**	**-1.0**	**0.115**
LAM60B exit	**MI-60**	**4.0**	**-1.0**	**0.115**
LAM60C entr	**MI-60**	**2.0**	**2.0**	**0.115**
LAM60C exit	**MI-60**	**2.0**	**2.0**	**0.115**
LAM62C entr	MI-62	5.0	0.0	0.220
LAM62C exit	MI-62	5.0	0.0	0.220
LAM62B entr	MI-62	4.0	-3.0	0.098
LAM62B exit	MI-62	4.0	-3.0	0.098
LAM62A entr	MI-62	2.0	-4.0	0.037
LAM62A exit	MI-62	2.0	-4.0	0.037
LAM10 entr	MI-10	0.0	7.5	0.043633
LAM10 exit	MI-10	0.0	7.5	0.043633
LAM222 entr	MI-22	-5.0	0.0	0.0
LAM222 exit	MI-22	-5.0	0.0	0.0
LAM321 entr	MI-32	12.0	0.0	0.0
LAM321 exit	MI-32	12.0	0.0	0.0
LAM40A entr	MI-40	-2.0	-3.0	0.220
LAM40A exit	MI-40	-2.0	-3.0	0.220
LAM40B entr	MI-40	-1.0	0.0	0.108
LAM40B exit	MI-40	-1.0	0.0	0.108
LAM40C entr	MI-40	2.5	-2.0	0.070
LAM40C exit	MI-40	2.5	-2.0	0.070
LAM52A entr	MI-52	2.54	0.0	0.220
LAM52A exit	MI-52	2.87	0.0	0.220
LAM52B entr	MI-52	2.87	0.0	0.098
LAM52B exit	MI-52	3.96	0.0	0.098
LAM52C entr	MI-52	3.98	0.0	0.037
LAM52C exit	MI-52	5.08	0.0	0.037

Table 4: Quadrupole displacements; MI60 compared to other locations.

name	location	horizontal	vertical
		mm	mm
IQB210U	**Q602**	**1.582**	**0.0**
IQB075U	**Q606**	**-1.9642**	**0.0**
IQD026U	**Q610**	**-1.708**	**0.0**
IQD041U	**Q612**	**0.0588**	**0.0**
IQB046U	**Q614**	**1.54**	**0.0**
IQD029U	Q618	-3.232	0.0
IQE134U	Q620	0.306	0.0
IQC024U	Q622	-3.257	0.0
IQD006U	Q641	0.0	0.0
IQG333U	Q101	0.0	0.0
IQB176U	Q103	0.0	0.0
IQD010U	Q218	0.0	0.0
IQC023U	Q220	0.0	0.0
IQB045U	Q222	0.0	0.0
IQC009U	Q319	0.0	0.0
IQB071U	Q321	0.0	0.0
IQD037U	Q323	0.0	0.0
IQD015U	Q340	-0.688	0.0
IQC035U	Q400	-3.078	0.0
IQE065U	Q402	-0.919	0.0
IQC036U	Q404	-3.041	0.0
IQD043U	Q406	0.0	0.0
IQD016U	Q518	-0.950	0.0
IQC022U	Q520	-1.927	0.0
IQE072U	Q522	0.287	0.0
IQD024U	Q524	-1.690	0.0
IQD018U	Q526	0.822	0.0

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Table 5: Corrector strength at injection and at 120 GeV.

name	location	length	B injection	B 120 GeV	system
		m	kG	kG	
H602	**Q602**	**0.3048**	**-0.151968**	**0.0**	
H606	**Q606**	**0.3048**	**0.195808**	**0.0**	**extraction**
H610	**Q610**	**0.3048**	**0.225459**	**0.0**	**to NuMI**
H612	**Q612**	**0.3048**	**-0.005774**	**0.0**	
H614	**Q614**	**0.3048**	**-0.155643**	**0.0**	
H618	Q618	0.3048	0.243483	0.0	antiproton
H620	Q620	0.3048	-0.015496	0.0	extraction
H622	Q622	0.3048	0.206837	0.0	
V641	Q641	0.3048	0.454612	1.914167	proton
V101	Q101	0.3048	-0.113542	-0.478074	injection
V103	Q103	0.3048	0.476582	2.006673	
H220	Q220	0.3048	-0.376349	-2.580411	antiproton
H222	Q222	0.3048	0.033086	0.226854	from recycler
H224	Q224	0.3048	-0.428911	-2.940797	
H224	Q224	0.3048	0.628655	0.0	
H226	Q226	0.3048	0.186812	0.0	Kick
H304	Q304	0.3048	1.037037	0.0	compensation
H318	Q318	0.3048	-0.158234	0.0	
H320	Q320	0.3048	-0.499033	0.0	
H320	Q320	0.3048	0.258827	2.65	proton
H322	Q322	0.3048	0.005413	0.055421	from recycler
H324	Q324	0.3048	0.360555	3.691542	
H340	Q340	0.3048	0.0	0.0	
H400	Q400	0.3048	0.223720	0.0	beam
H402	Q402	0.3048	0.014799	0.0	abort
H404	Q404	0.3048	0.219101	0.0	
H406	Q406	0.3048	0.0	0.0	
H518	Q518	0.3048	0.0	0.0	proton
H520	Q520	0.3048	0.231776	0.0	extraction
H522	Q522	0.3048	-0.024367	0.0	and
H524	Q524	0.3048	0.262963	0.0	antiproton
H526	Q526	0.3048	0.0	0.0	injection
adjustment at HP522 by 3.37 mm gives -13.8 mm at HP522 with quad bump					
H520	Q520	0.3048	0.0	0.84887	
H522	Q522	0.3048	0.0	-0.09168	
H524	Q524	0.3048	0.0	0.96126	

[i] A. Drozhdin, A. Marchionni, et.al, Document in Preparation.
[ii] I.S.Baishev, A.I.Droxhdin and N.V.Mokhov, “STRUCT Program User’s Reference Manual”, SSCL-MAN-0034 (1994).
[iii] S. Mishra, Communication to NuMI Project, March 2002.
[iv] C. Jensen, Single Turn Extraction Kicker Specifications, January 2001.
[v] C. Jensen
[vi] D. Johnson, S. Mishra, private communication.